HETEROGENEITY OF REMNANT MAGNETISM IN ALH84001: PETROLOGIC CONSTRAINTS.

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Natural remnant magnetism (NRM) in ALH84001 is held in pyrrhotite in a wide range of orientations [1-3]. This spread of NRM orientations has been interpreted to mean that a uniform magnetic field was trapped early in scattered pyrrhotite grains, which were subsequently rotated relative to each other in a brecciation. Thereafter, the NRM-carrier pyrrhotites could not have been hotter than 40°C. Rock textures do not support this interpretation, but indicate several strong thermal events after the only deformation that produced significant grain rotations [4]. Thus, the scattered NRM directions must have been acquired after brecciation. Just how remains a mystery.

Introduction: The magnetic properties of martian meteorite ALH84001 have important implications for the reality of putative traces of ancient Martian life in ALH84001 [1,5], for the thermal history of ALH84001 [4], and for the timing and strength of a Martian planetary magnetic field [6]. J. Kirschvink and co-workers have shown that a strong NRM is trapped in sub-micron grains of pyrrhotite, $Fe_{1-x}S$, in pyroxene in ALH84001 [1-3]. The NRM orientation varies within the rock – fragment preserve NRM at orientations significantly different from those in neighboring fragments. In the best documented case [1], pyroxene grains less than 1 mm apart preserve NRM dipoles oriented 75° apart. Moreover, the pyrrhotite carrier of the NRM is easily reset under heat – to preserve the observed NRMs, the carrier pyrrhotites could not have ever been warmer than 40°C since NRM acquisition.

To explain these results, Kirschvink, Weiss, et al. suggest that the NRM directions in ALH84001's pyrrhotite grains were once oriented in parallel, having trapped a uniform magnetic field permeating the rock [1-3]. After entrapment of the NRM, ALH84001 was broken (brecciated) into small fragments which were rotated significantly with respect to each other. During this brecciation, the NRM-carrying pyrrhotite never became warmer than 40°C. The rock was subsequently resolidified (T<40°C) to the form now seen. Nor did ejection from Mars and transit to Earth allow T to exceed 40°C [2,3].

Petrology. The interrelationships and compositions of mineral grains in ALH84001 bespeak a history of repeated thermal and deformational events [4]. ALH84001 was originally (~4.5 Ga [7]) a cumulate igneous rock, principally cm-sized grains of orthopyroxene and chromite (Fig. 1). In deformation event D1 (probably related to an impact event [4]), the cumulate rock was broken and intensely deformed to produce the fine-grained granular bands (Figs. 1-3).

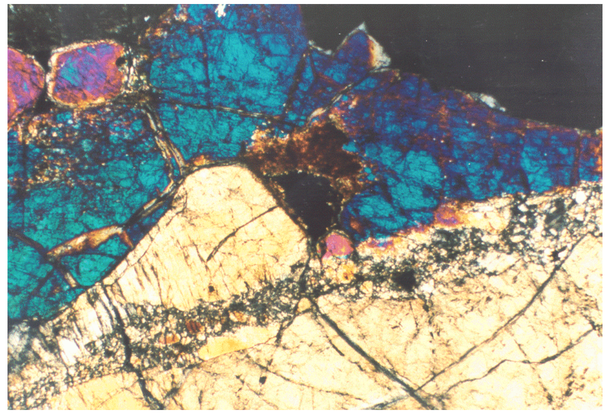

Figure 1. Typical area, ALH84001,36 (X-polars, FOV ~3 mm). Three pyroxene grains (yellow, blue-green, purple) in typical cumulate texture. Granular band (lower-left to center-right) displaces boundaries of cumulate grains without rotating them.

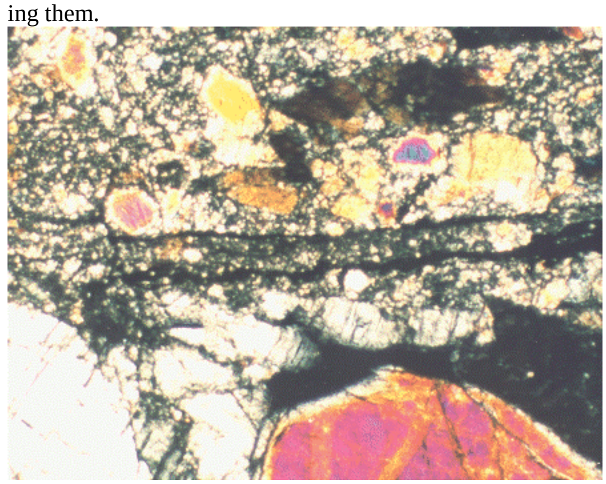

Figure 2. Unusual granular band, ALH84001,36 (X-polars, FOV ~1.5 mm). Cumulate pyroxene grains (red, white) at bottom. Above horizontal black lines (stringers of chromite), rotated pyroxene grains appear as isolated colored patches.

These granular bands were then recrystallized in event Cγ, interpreted as high-temperature annealing [4] (Fig. 3). Before the carbonate globules formed at ~3.9 Ga [8] in event Cδ, ALH84001 experienced shock-metamorphic event D2, which produced maskelynite or melt from plagioclase. After formation of the carbonates, ALH84001 suffered yet another shock-metamorphism, event D3, which melted the plagioclase glass and dispersed fragments of the carbonate globules within that melt. Formation of the heterogeneous NRM directions did not fit in this framework. Treiman [4] accommodated it in a later low-temperature brecciation D4, even in the absence of other evidence for a late-stage brecciation.

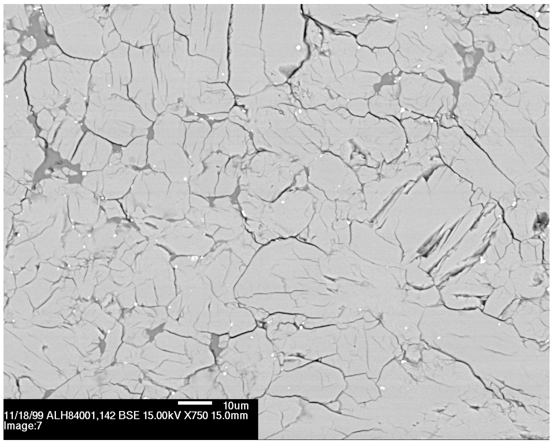

Figure 3. Granular band, secondary electron image (SEM), section ALH84001, 142. Pyroxene is gray, chromite is bright dots, cracks and feldspathic glass are dark. Note absence of intergranular void spaces, smooth grain contacts, and irregular overall shapes of grains.

Reconciliation? The NRM data [1-3] must be accepted, but their present interpretation is at odds with the present interpretation of the mineralogy and petrology of ALH84001.

1). Rotations? Weiss et al. [3] infer that NRM directions in ALH84001 were dispersed during the D1 deformation event, which was the only deformation that produced significant and common rotations of pyroxene grains. Even so, the main effect of D1 was not rotation of discrete fragments, but production of intensely deformed zones that cross-cut the rock without having produced significant rotation (Fig. 1; Fig. 2 of [9]; Fig. 2b of [4]). Within the granular bands, small fragments were probably rotated significantly (Fig. 2; Fig. 3 of [9]; Fig. 2a of [e]) larger fragments were rotated only in atypical regions (Fig. 1).

2). Temperature? If the NRM were acquired before deformation D1 [3], then the pyrrhotite grains that carry the NRM could not have been heated above 40°C in their whole subsequent history. This strict thermal constraint seems to be at significant variance with the petrologic evidence, notably on events D1 and Cγ.

Event D1 saw production of the granular zones (Figs. 1-3) and brittle deformation of much of its igneous-textured pyroxene [4]. D1 was at high strain-rate, with concomitant brittle effects, granulation, and friction heating, possibly to >1300°C [10]. With so much heat localized in the granulated zones, it seems unlikely (but perhaps not impossible) that most of ALH84001 remained below 40°C following D1.

Next was Cγ, possibly the thermal aftermath of D1 [4], which is recognized by textural and chemical changes in the granular bands and the igneous-textured pyroxenes (Fig. 3; Fig 5 of [9], Fig. 3 of [4]). As shown in these images, granular bands are compact masses of pyroxene grains with lesser proportions of feldspathic glass, chromite, and sulfide. The pyroxene grains have smooth, rounded boundaries with each other at scales of a few µm, although the grains' overall shapes are irregular at scales of 10s of µm – a pattern called decussate [11]. This textural pattern is typical of thermal metamorphism [11], and mineral compositions in the granular bands and the bulk rock are consistent with metamorphic equilibrium at T~875°C [4,9,12]. This high temperature would have obliterated and reset NRM in pyrrhotite. Textural patterns like this can be produced at high pressure and low temperature in the laboratory, particularly for relatively plastic materials (which pyroxene is not). However, in the geothermal gradient of Mars, high P implies high T, and again the pyrrhotite would not remain colder than 40°C.

Acquisition of NRM. Weiss et al. [3] suggest that the NRM was acquired early, just after original formation of the original cumulate. Afterwards, the rock never experienced T>40°C, even in the major deformation event D1. Textural and mineral chemical data are not consistent with this interpretation [4,9,12]. Rather, they imply that ALH84001 was likely warmer than 40°C during the major brecciation D1, the subsequent annealing Cγ, and probably several later events (shock metamorphism D2, possibly carbonate formation Cδ [12], and shock metamorphism D3).

However, acquisition of NRM after D1 presents serious problems. It is not clear how the wide range of NRM orientations [a-c] could have been trapped in a single rock within mm of each other. Two (unimpressive) possibilities suggest themselves. First, could the NRM have been produced by a turbulent electromagnetic pulse (EMP) associated with one of the later shock events? Second, could the pyrrhotite have magnetized spontaneously in random orientations, perhaps as it formed, in the absence of a significant applied (planetary field)? Neither possibility is currently supportable, and much more work is needed.

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[1] Kirschvink J. et al. (1997) Science 275, 1629. [2] Weiss B.P. et al. (1999) 5th Intl. Mars Conf. Abstr. 6204. [3] Weiss B.P. et al. (1999) EOS (Trans. AGU) F94. [4] Treiman A.H. (1998) M&PS 33, 753. [5] McKay D. et al. (1996) Science 273, 924. [6] Acuña M.H. et al. (1999) Science 284, 790. [7] Nyquist et al. (1995) LPSC XXVI, 1065. [8] Borg L.E. et al. (1999) Science 286, 90. [9] Treiman A.H. (1995) Meteoritics 30, 294. [10] van der Bogert C.H. and Schultz P.H. (1998) L.P.I. Contrib. # 956. 56. [11] Spry A. (1969) *Metamorphic Textures*. [12] Shearer et al. (1999) M&PS 34, 331.